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6. AUTHORS X. Rong Li, Vesselin P. Jilkov, Huimin Chen			5d. PROJECT NUMBER		
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14. ABSTRACT The project has made important accomplishments in the following inter-related areas centered on target information processing by joint decision and estimation: (a) theory and algorithm development for joint decision and estimation; (b) target information processing, particularly for target tracking under equality and/or inequality constraints; (c) theory and algorithm development for data fusion for estimation; (d) UAV team path optimization for search and track; (e) variable-structure algorithms and model-set design methods for multiple-model approach					
15. SUBJECT TERMS target information processing, estimation fusion, estimation and filtering, multiple-model estimation, performance evaluation, UAV path optimization					
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Report Title

Final Report

ARO project (ARO W911NF-08-1-0409)

Target Information Processing: A Joint Decision and Estimation Approach

ABSTRACT

The project has made important accomplishments in the following inter-related areas centered on target information processing by joint decision and estimation: (a) theory and algorithm development for joint decision and estimation; (b) target information processing, particularly for target tracking under equality and/or inequality constraints; (c) theory and algorithm development for data fusion for estimation; (d) UAV team path optimization for search and track; (e) variable-structure algorithms and model-set design methods for multiple-model approach to target information processing; and (f) performance and credibility evaluation of decision and estimation algorithms. Some of these accomplishments have fundamental theoretical value and some others have important practical significance. Most of the accomplishments have been disseminated in the form of publication, which includes 23 journal articles (16 appeared or to appear and 7 submitted), 55 conference proceedings papers (42 appeared and 13 submitted), and 3 book chapters (2 appeared and 1 to appear).

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
2012/03/29 2: 71	A. Bashi, V. P. Jilkov, X. R. Li. Fault detection for systems with multiple unknown modes and similar units, IEEE Transactions on Control Systems Technology, (09 2011): 0. doi:
2012/03/29 2: 70	X. R. Li, Z.-L. Zhao, X.-B. Li . Evaluation of estimation algorithms—part II: credibility tests, IEEE Transactions on Systems, Man, and Cybernetics—Part A: Systems and Humans, (01 2012): 0. doi:
2012/03/29 2: 69	Y.-M. Wang, X. R. Li. Distributed estimation fusion under unknown cross-correlation, IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS , (01 2012): 0. doi:
2012/03/29 2: 68	Y.-X. Gao, X. R. Li. Optimal linear fusion for smoothed state estimates, IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS , (04 2012): 0. doi:
2012/03/29 2: 55	H. Chen. A multiple model prediction algorithm for CNC machine wear PHM, , International Journal of Prognostics and Health Management, 2(2), 2011., (11 2011): 0. doi:
2012/03/29 2: 9	YIMIN WANG, X. RONG LI. Distributed estimation fusion under unknown cross-correlation, IEEE Transactions on Aerospace and Electronic Systems, (01 2012): 0. doi:
2011/11/05 1: 7	X. Rong Li, Huimin Chen, Deqiang Gan, Jiaju Qiu, Xiaomeng Bian. Joint estimation of state and parameter with synchrophasors—part II: parameter tracking, IEEE Transactions on Power Systems, (08 2011): 1209. doi:
2011/11/05 1: 6	Xiaomeng Bian, X. Rong Li, Huimin Chen, Deqiang Gan, Jiaju Qiu. Joint estimation of state and parameter with synchrophasors—part I: State Tracking, IEEE Transactions on Power Systems, (08 2011): 1196. doi:
2011/11/05 1: 4	Anwer Bashi, Vesselin P. Jilkov, X. Rong Li. Fault detection for systems with multiple unknown modes and similar units, IEEE Transactions on Control Systems Technology, (11 2011): 957. doi:
2011/11/05 1: 3	JIAN LAN, X. RONG LI, CHUNDI MU. Best model augmentation for variable-structure multiple-model estimation, IEEE Transactions on Aerospace and Electronic Systems, (07 2011): 2008. doi:
2011/11/05 1: 2	Zhansheng Duan, X. Rong Li. Lossless linear transformation of sensor data for distributed estimation fusion, IEEE Transactions on Signal Processing, (01 2011): 362. doi:

TOTAL: 11

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
2011/11/05 11:13	Ryan R. Pitre , X. Rong Li , Donald R. DelBalzo. Route planning for search and track missions by a UAV team, IEEE Transactions on Aerospace and Electronic Systems, (06 2012): 0. doi:
2011/11/05 11:12	Jian Lan, X. Rong Li, Vesselin P. Jilkov, Chundi Mu. Second-order Markov chain based multiple-model algorithms for maneuvering target tracking, IEEE Transactions on Aerospace and Electronic Systems, (03 2012): 0. doi:
2011/11/05 11:11	Yongxin Gao, X. Rong Li. Optimal linear fusion for smoothed state estimates, IEEE Transactions on Aerospace and Electronic Systems, (05 2012): 0. doi:
2011/11/05 11:10	X. Rong Li, Chongzhao Han, Zhansheng Duan, Yongqi Liang. A general method for model-set design, IEEE Transactions on Aerospace and Electronic Systems, (02 2012): 0. doi:
2011/11/05 11:08	X. Rong Li, Zhanlue Zhao, Xiao-Bai Li. Evaluation of estimation algorithms—part II: credibility tests, IEEE Transactions on Systems, Man, & Cybernetics, (12 2011): 0. doi:

TOTAL: 5

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>	<u>Paper</u>
2012/03/29 2: 62	V. P. Jilkov, J. Wu , H. Chen. Parallel Particle Filter Implementation on Cluster Computer for Satellite Tracking Application, In: Proc. 4th International Conference on Neural, Parallel & Scientific Computations,Atlanta, GA, USA. 2010/08/11 01:00:00, . : ,
2012/03/29 2: 61	V. P. Jilkov, J. R. Katkuri, H. K. Nandiraju. Design of Bayesian Signal Detectors using Gaussian-Mixture Model, Proc. 42nd IEEE Southeastern Symposium on System Theory,Tyler, TX, USA. 2010/03/07 01:00:00, . : ,
2012/03/29 2: 60	H. Chen, G. Chen, E. Blasch, P. Douville, K. Pham. Information theoretic measures for performance evaluation and comparison, Proc. 12th International Conf. Information Fusion, Seattle, WA, USA. 2009/07/06 01:00:00, . : ,
2012/03/29 2: 59	H. Chen, Z. Zhao. An information theoretic viewpoint on haplotype reconstruction from SNP fragments, Proc. 3rd Int. Conf. on Bioinformatics and Biomedical Engineering, Beijing, China. 2009/06/20 01:00:00, . : ,
2012/03/29 2: 58	H. Chen, D. Shen, G. Chen, E. Blasch, K. Pham. Tracking evasive objects via a search allocation game, Proc. of American Control Conf., Baltimore, MD, USA. 2010/06/30 01:00:00, . : ,
2012/03/29 2: 22	Vesselin P. Jilkov , Jiande Wu. Implementation and Performance of a Parallel Multitarget Tracking Particle Filter, Proc. 14th International Conference on Information Fusion, Chicago, IL, USA. 2011/07/05 01:00:00, . : ,

TOTAL: 6

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Manuscripts:

Books

<u>Received</u>	<u>Paper</u>
2012/04/04 2: 79	H. Chen, Z. Zhao, K. Zhang, D. Zhu. New aspects of haplotype inference from SNP fragments, ABCDE: iConcept Press, (06 2010)
2012/03/30 0: 80	G. Chen, D. Shen, E. Blasch, K. Pham, H. Chen. Orbital evasive target tracking and sensor management, Springer Lecture Notes in Control and Information Sciences: Springer, (06 2010)
2011/11/05 1: 23	A. Bashi, V. P. Jilkov, X. R. Li. Nonlinear estimation and fault detection for large scale industrial HVAC systems, New York?: Nova Publisher, (05 2012)

TOTAL: 3

Patents Submitted

Patents Awarded

Awards

The PI, Dr. X. Rong Li, was selected as Chancellor's University Research Professor by the University of New Orleans in the second year of this project, which is one of the highest academic honors that the University of New Orleans can give.

The two co-PIs, Drs. Vesselin Jilkov and Huimin Chen, were both granted tenure and promoted to Associate Professor by the University of New Orleans in the second year of this project.

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Ashwini Amara	1.00	
Sowmya Bandrupalli	0.50	
Xiaomeng Bian	0.50	
Yangsheng Chen	1.00	
Zhansheng Duan	0.50	
Jaipal Katkuri	0.50	
Gang Liu	0.30	
Ryan Pitre	0.50	
Rastin Rastgoufard	0.50	
Harika Rao Vamulapalli	0.30	
FTE Equivalent:	5.60	
Total Number:	10	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
X. Rong Li	0.10	
Vesselin P. Jilkov	0.10	
Huimin Chen	0.10	
FTE Equivalent:	0.30	
Total Number:	3	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Sowmya Bandarupalli
Ashwini Amara
Harika Rao Vamulapalli
Jaipal Katkuri
Yangsheng Chen
Gang Liu

Total Number:

6

Names of personnel receiving PhDs

NAME

Zhansheng Duan
Ryan Pitre

Total Number:

2

Names of other research staff

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Selected Accomplishments

Joint Decision and Estimation

With a few exceptions that involve decision and estimation separately, most target information processing problems require joint decision and estimation (JDE). The underpinning of our research is a new paradigm for an integrated approach to JDE, based on a novel Bayesian formulation, and an optimal solution in this paradigm. The main advantage of this approach is that the problems of decision and estimation are solved jointly, rather than separately or in two stages as in the existing approaches. Not only does it beat the traditional decide-then-estimate or estimate-then-decide approaches, but it also provides additional strengths and flexibilities that are important to handle many target information processing problems.

Significant accomplishments have been made on this topic. More specifically, we have proposed an intuitively appealing and generally applicable objective function (Bayes risk) as the optimality criterion for the JDE problem. Based on the proposed Bayes risk, we have formulated the JDE problem mathematically in a general, flexible Bayesian setting, which is capable of handling most practical JDE problems, especially problems of target information processing. In this general, flexible setting we have derived the optimal solution to the JDE problem theoretically. Further, we have developed an optimal, iterative JDE algorithm based on the above optimal theoretical solution. We have also recognized a general method of making the optimal decision efficiently.

JDE is for solving problems involving inter-dependent decision and estimation and was proposed recently by us based on a generalized Bayes risk. Our above JDE algorithm processes data in a batch manner. This batch method is computationally inefficient or infeasible for many dynamic JDE problems where measurements are made available sequentially. Therefore, we proposed a recursive version of the JDE algorithm, which fits the dynamic JDE problems more naturally and inherits JDE's theoretical superiorities. Further, we also proposed a joint performance measure in the measurement space for dynamic JDE problems. To our knowledge, this is the only performance evaluation framework currently available for JDE evaluation.

For the JDE approach of this project, we have applied it to several problems in different areas. We have developed algorithms for joint identification and tracking of multiple chemical, biological, radiological, nuclear, and explosive (CBRNE) clouds based on sparsity pursuit. We have also developed procedures for joint estimation of state and parameter in power systems using synchrophasor measurements.

Target Information Processing

Target information processing refers to processing of information concerning an uncertain number of targets in an uncertain environment using uncertain, imprecise, and/or vague data from single or multiple sources. It includes target detection, discrimination, classification, recognition, identification, as well as tracking. Many target information processing problems involve both estimation (i.e., approximate a continuous-valued quantity) and decision (i.e., choose one from a discrete set of candidates). Decision in this sense includes detection, discrimination, classification, recognition, identification, selection, association, ranking, hypothesis testing, matching, etc. Parameter estimation, signal, image, or state estimation, prediction, filtering, smoothing, forecasting, and regression are examples of estimation. Target detection, discrimination, classification, recognition, and identification are basically decision problems, which often contain embedded estimation sub-problems. Target tracking are primarily estimation problems with embedded decision sub-problems.

We have completed two important parts of an ongoing in-depth up-to-date survey on maneuvering target tracking: (a) models of ballistic and space targets and (b) nonlinear filtering techniques. The nonlinear filtering part consists of three subparts. This series has already made considerable impact on target tracking research and development. In addition, we have developed nearly optimal algorithms for target tracking using range and direction cosine measurements, which is a nonlinear filtering problem whose optimal solution is beyond practical region. Other significant contributions include: (a) development of hybrid grid multiple-model estimation approach and its application to maneuvering target tracking; (b) development, implementation, and performance study of several parallel particle filtering algorithms for real-time satellite tracking, and joint multitarget probability density tracking of ground targets (track-before-detect) using computer cluster and graphics processing unit.

Estimation and filtering theory is one of the most important foundations of target information processing. We have made significant contributions in this aspect. More specifically, we have developed a new framework for state estimation with point and set measurements that can handle effectively many diverse applications, including particularly many practical problems in target information processing. Highly related with this new framework, we also investigated estimation and filtering for Gaussian variables with linear inequality constraints. This has important applications in ground (especially on-road) target tracking.

The states of some dynamic systems satisfy certain constraints arising from physical laws, mathematical properties, or practical constraints. A typical example is ground target tracking on a road network. We have made significant contributions in several

aspects of this important topic. First, we have proposed several algorithms in different forms of the linear minimum mean square estimator for this problem. They are all optimal in the linear class. Second, we have developed a general method to construct an unconstrained dynamic model that is mathematically equivalent to the original system with constraints, thus simplifying the constrained problem to an unconstrained problem. This model has several important desirable properties, including clear physical interpretation and high computational efficiency. Third, we have made an important finding: under certain conditions, although equality constraints are indispensable in the evolution of the state, update by them is redundant in optimal filtering; however, if there is model mismatch, update by equality constraints is necessary and helpful. Fourth, unlike the existing system conversion based design techniques, we propose a new systematic way to design and analyze linear equality constrained linear dynamic systems through a direct elimination technique, where the desired model class is given and only the distribution of the initial state and driven process noise needs to be determined. This method is comparatively much easier. We also found that the existing formulations of linear equality constrained linear dynamic systems only cover a small part of the whole class.

Based on our work in these areas, we have also developed algorithms and designs for aided strapdown inertial navigation for autonomous underwater vehicles. This was a practical project funded by the Naval Oceanographic Office.

Data Fusion for Estimation

Estimation fusion is data fusion for the purpose of estimating some quantity, usually a parameter or a process. It is an essential part of target information processing when multiple sensors are used. Abundant results in this area have been obtained. They include several aspects.

- Optimal fusion requires knowledge of cross-correlation. Unfortunately, this knowledge is sometimes unavailable in practice. In view of this, we have developed three fault-tolerant fusion rules for this case: fast covariance intersection, generalized convex combination, and analytic center approach.
- We have proposed several compression rules for sensor data based on which optimal distributed fusion will have performance that is globally optimal under fairly general conditions.
- We have developed optimal LMMSE fusion in the form of quasi-tracklets to handle cross-correlated cases, along with analysis of its performance and presentation of necessary and sufficient condition for its optimality.
- Estimation fusion for the case of multiple dynamic and/or measurement models was never considered before due to its complexity. We have successfully developed several such fusers.
- Almost all existing fusion results rely on some level of probabilistic or statistical description of the problem, which is not available or appropriate in some cases. With this understanding, we proposed a new formulation in the H-infinity setting, which is robust against descriptions and assumptions, and successfully developed several corresponding rules for centralized and distributed fusion, which is applicable even to nonlinear delayed systems with multiple sensors.
- Besides fusion results for filtering, we have also obtained theoretical results for fusion for optimal smoothing, which has been largely overlooked so far by the fusion community.

UAV Team Path Optimization for Search and Track

To better serve the Army's mission, one application focus of the project is path planning of a team of unmanned aerial vehicles (UAV) for joint detection, localization, and tracking of multiple targets. Another is ground target tracking—track an uncertain number of possibly crossing targets using data transmitted from multiple sensors (e.g., imagers and radars) onboard a moving platform as well as topographic information such as road maps.

Most UAV team missions have a dual purpose of search and surveillance, which entails not only finding, but also monitoring of targets, including their locations and motions. Among the central topics of UAV missions is path planning for search and surveillance. It is vastly different from the traditional path planning (e.g., in robotics), which is largely a “how-to-go-from-A-to-B” problem. Traditional search or tracking theoretic approaches based on optimizing detection probability or estimation error would not meet the diverse, competing needs of a UAV mission. Unlike existing path planning of a cooperative UAV team, which handles the competing objectives in a piecemeal manner, we took a systematic JDE approach: we proposed a solution based on the introduction of a new performance index—gain in the information value—which permits naturally joint optimization of the objectives of target detection, target tracking, and vehicle survivability nicely for search and track missions.

More recently, we have obtained significant theoretical results for dynamic re-planning of the UAV team path for detection, localization, and tracking that is capable of adapting to real-time changes in the command, intelligence, environment, etc. These results are significantly more solid than existing ones. In a dynamic situation, events that call for a change of the plan may occur, including the arrival of a new command or intelligence, detection of a new target, loss of a UAV, a sudden change of weather, etc. Therefore, an appropriate time horizon for re-planning must be determined. If it is too long or too short, the updated plan may be poor. There is little research, if any, regarding the determination of the optimal planning horizon. We have initiated a theoretical study of this important topic. Our work presents a planning horizon that is optimal in the sense of minimizing errors in planning time. It is intended for the use in mission planning but has many other applications.

Technically, UAV path planning for target detection, localization, and tracking is a problem of constrained multiple-objective optimization. As is well known, there is an optimal set (i.e., Pareto front) in which each point corresponds to a certain tradeoff among the values of the objective functions. Solutions to such a problem are not unique in general. Which of the many Pareto optimal points is the “best trade-off”? A decision is needed as to which Pareto optimal point provides the best tradeoff among all alternatives. A natural approach is to optimize a convex combination of the individual objectives. We have developed such a solution for cooperative UAV path optimization, along with an efficient method of getting the weights from the Pareto optimal points. We are developing methods based on a special scalar objective function that suits particularly well to our problem of UAV path optimization for joint detection, localization, and tracking of multiple targets.

Multiple-Model Approach

The multiple-model (MM) approach can be treated as a special case of the joint decision and estimation (JDE) approach, which is the focus of this project. It provides the state-of-the-art solutions to many problems involving estimation, filtering, control, decision, and/or modeling. It has three generations: autonomous MM, cooperating MM, and variable-structure MM (VSMM), of which the VSMM is the most advanced and powerful. Significant results have been obtained in several aspects.

- We have developed three new VSMM approaches: (a) best-model augmentation (BMA), (b) hybrid grid, and (c) second-order Markov chain. BMA is a general and promising new VSMM algorithm. It is a generalization of the well-regarded expected-mode augmentation (EMA) algorithm developed by us before. It is applicable whenever EMA is and they are virtually the same. BMA still applies when EMA does not, such as when models have different structures. The hybrid-grid approach uses a model set that is a combination of a fixed coarse grid and an adaptive fine grid. The second-order Markov chain based multiple-model algorithms developed is particularly suitable for maneuvering target tracking.
- Perhaps the most important task in the application of the MM approach is the design of model set. We have also made significant progress in this aspect. We have proposed two model-set design methods. The uniform model set design is based on number theory and has general applicability. The second, moment-matching based approach is particularly suited to the hybrid-grid approach to MM estimation developed recently.
- Taking advantage of the great power of the MM approach, we have also formulated the problem of fault detection and isolation in the MM setting and provided a solution that outperforms by far existing ones. This has been done for vastly different applications: (a) sensor, actuator, or system faults of an aircraft (b) heating, air conditioning, and ventilation (HAVC) in building automation and (c) machine wear prognostics and remaining useful life prediction.
- In addition, we have obtained significant results for distributed MM fusion, that is, fusing local estimates obtained based on multiple dynamic models.

Evaluation of Decision and Estimation Algorithms

Science and engineering abound in algorithms for decision or estimation. However solid such an algorithm is in theory, its performance and characteristics must be evaluated in practice to serve a number of purposes, such as verification of its validity, demonstration of its performance, and comparison with other solutions.

We have developed a novel, theoretically solid approach to performance evaluation that is general, comprehensive, and straightforward to implement without the need to know the ground truth. It can always rank very different decision algorithms objectively; it has no difficulty for cases with two or more choices (or hypotheses), misspecification (i.e., the truth is not one of the hypotheses), and/or where hypotheses are composite (i.e., having unknown parameters); and it does not need to know the functional form of the truth or hypotheses. This is a very significant development. It is potentially a breakthrough in decision performance evaluation. Past and existing measures of decision performance are seriously flawed or limited. Our method is the only one known to us that overcomes many difficulties (including all those listed above) naturally and easily.

We have developed an array of metrics that measure absolute or relative performance of estimation. They suit different applications. We have clarified widespread misuse of and misconception about the most popular estimation metric: root-mean-square error. We have also introduced an important concept of optimism, pessimism, and neutralism to characterize many estimation performance metrics regarding whether they focus on good or bad performance. We have also initiated the study of comprehensive measures of estimation performance evaluation. The practical value of these largely theoretical developments has been quickly recognized by the target information processing community. For example, based on his team's comparative studies, Dr. Erik Blasch of Air Force Research Laboratory appraised highly of the practical value of our work on performance evaluation metrics for data fusion and target tracking and classification.

Most estimators and filters provide assessments of their own estimation errors, often in the form of mean-square error and bias. Are these self-assessments trustable? What is the degree to which they are trustable? We have raised such questions formally, referred to as credibility of estimators, formulated the problem theoretically, and provided two types of solutions: credibility tests for qualitative questions of the first kind and credibility measures for quantitative questions of the second kind. These results are significant. They address an important practical problem of estimation that has been largely overlooked in

theory but are badly needed in practice. We have also shown that one of the credibility measures developed is truly a distance metric and have good application in many areas outside credibility evaluation, such as statistics, data fusion, matrix theory, and general data driven performance evaluation.

We also applied theoretical study in performance metrics and statistical inference algorithms to haplotype inference problem in bioinformatics, orbital evasive target tracking and sensor management in space situational awareness, joint identification and tracking of contaminate clouds, remaining useful life prediction of battery and other mission critical components in fault prognosis.

Technology Transfer:

We have been and are collaborating with several small business companies for technology transfer. Several joint SBIR/STTR proposals for such collaboration have been submitted, based partially on results from a former ARO project and this ARO project. Two of them were successful:

 “Multiple Target Tracking of Objects Exhibiting Significant Nonlinearities,” jointly with ObjectVideo, Inc., funded by Air Force Research Lab in the amount of \$150,000 for Phase I.

 “An Integrated Constellation Sensor Simulation Environment for Airborne ISR,” jointly with DCM Research Resources, LLC, funded by the Air Force Research Lab in the amount of \$100,000 for Phase I.

Research results of a former ARO project and this ARO project have been applied to this SBIR project. We have active ongoing collaboration with many researchers elsewhere, including DoD labs, DoE lab, and numerous companies. We are actively seeking collaboration with researchers at Army, Navy, and Air Force R&D facilities.

Based on the research of this ARO project, we have also secured the following funded research projects:

 A research project titled “Coordinated Search and Surveillance by a UAV Team” on the development of flight path optimization and control of a coordinated UAV team for search and track missions, funded by the Department of Homeland Security in the amount of \$200,000 for 20 months. The project, led by us, is a team work with QinetiQ North America and the Ben-Gurion University of Israel. The cornerstone of the project is the introduction of an expected information gain as the objective function. It is a special case of the general JDE method developed in the ARO project, tailored particularly for UAV search and track missions.

 The study on nonlinear filtering techniques, particularly its application in maneuvering target tracking, supported by this ARO project forms part of the basis for the three-year project titled “High Performance Parallel & Distributed Algorithms for Nonlinear Particle Filtering,” funded by Louisiana Board of Regents in the amount of \$109,143.

 Based on our work in these areas, we have developed algorithms and designs for aided strapdown inertial navigation for autonomous underwater vehicles. This was a practical project funded by the Naval Oceanographic Office in the amount of \$100,000 for one year. The performance evaluation results obtained in this project was critical in evaluating the navigation performance of this project.

Technology Transfer

Final Report
ARO project (ARO W911NF-08-1-0409)
Target Information Processing: A Joint Decision and Estimation Approach

X. Rong Li, Vesselin P. Jilkov, Huimin Chen

March 29, 2012

Subject terms: target information processing, estimation fusion, estimation and filtering, multiple-model estimation, performance evaluation, UAV path optimization

Approved for Public Release; Distribution Unlimited

Abstract

The project has made important accomplishments in the following inter-related areas centered on target information processing by joint decision and estimation: (a) theory and algorithm development for joint decision and estimation; (b) target information processing, particularly for target tracking under equality and/or inequality constraints; (c) theory and algorithm development for data fusion for estimation; (d) UAV team path optimization for search and track; (e) variable-structure algorithms and model-set design methods for multiple-model approach to target information processing; and (f) performance and credibility evaluation of decision and estimation algorithms. Some of these accomplishments have fundamental theoretical value and some others have important practical significance. Most of the accomplishments have been disseminated in the form of publication, which includes 23 journal articles (16 appeared or to appear and 7 submitted), 55 conference proceedings papers (42 appeared and 13 submitted), and 3 book chapters (2 appeared and 1 to appear).

Selected Accomplishments

Joint Decision and Estimation

With a few exceptions that involve decision and estimation separately, most target information processing problems require *joint decision and estimation (JDE)*. The underpinning of our research is a new paradigm for an integrated approach to JDE, based on a novel Bayesian formulation, and an optimal solution in this paradigm. The main advantage of this approach is that the problems of decision and estimation are solved jointly, rather than separately or in two stages as in the existing approaches. Not only does it beat the traditional decide-then-estimate or estimate-then-decide approaches, but it also provides additional strengths and flexibilities that are important to handle many target information processing problems.

Significant accomplishments have been made on this topic. More specifically, we have proposed an intuitively appealing and generally applicable objective function (Bayes risk) as the optimality criterion for the JDE problem. Based on the proposed Bayes risk, we have formulated the JDE problem mathematically in a general, flexible Bayesian setting,

which is capable of handling most practical JDE problems, especially problems of target information processing. In this general, flexible setting we have derived the optimal solution to the JDE problem theoretically. Further, we have developed an optimal, iterative JDE algorithm based on the above optimal theoretical solution. We have also recognized a general method of making the optimal decision efficiently.

JDE is for solving problems involving inter-dependent decision and estimation and was proposed recently by us based on a generalized Bayes risk. Our above JDE algorithm processes data in a batch manner. This batch method is computationally inefficient or infeasible for many dynamic JDE problems where measurements are made available sequentially. Therefore, we proposed a recursive version of the JDE algorithm, which fits the dynamic JDE problems more naturally and inherits JDE's theoretical superiorities. Further, we also proposed a joint performance measure in the measurement space for dynamic JDE problems. To our knowledge, this is the only performance evaluation framework currently available for JDE evaluation.

For the JDE approach of this project, we have applied it to several problems in different areas. We have developed algorithms for joint identification and tracking of multiple chemical, biological, radiological, nuclear, and explosive (CBRNE) clouds based on sparsity pursuit. We have also developed procedures for joint estimation of state and parameter in power systems using synchrophasor measurements.

Target Information Processing

Target information processing refers to processing of information concerning an uncertain number of targets in an uncertain environment using uncertain, imprecise, and/or vague data from single or multiple sources. It includes target detection, discrimination, classification, recognition, identification, as well as tracking. Many target information processing problems involve both estimation (i.e., approximate a *continuous*-valued quantity) and decision (i.e., choose one from a *discrete* set of candidates). Decision in this sense includes detection, discrimination, classification, recognition, identification, selection, association, ranking, hypothesis testing, matching, etc. Parameter estimation, signal, image, or state estimation, prediction, filtering, smoothing, forecasting, and regression are examples of estimation. Target detection, discrimination, classification, recognition, and identification are basically decision problems, which often contain embedded estimation sub-problems. Target tracking are primarily estimation problems with embedded decision sub-problems.

We have completed two important parts of an ongoing in-depth up-to-date survey on maneuvering target tracking: (a) models of ballistic and space targets and (b) nonlinear filtering techniques. The nonlinear filtering part consists of three subparts. This series has already made considerable impact on target tracking research and development. In addition, we have developed nearly optimal algorithms for target tracking using range and direction cosine measurements, which is a nonlinear filtering problem whose optimal solution is beyond practical region. Other significant contributions include: (a) development of hybrid grid multiple-model estimation approach and its application to

maneuvering target tracking; (b) development, implementation, and performance study of several parallel particle filtering algorithms for real-time satellite tracking, and joint multitarget probability density tracking of ground targets (track-before-detect) using computer cluster and graphics processing unit.

Estimation and filtering theory is one of the most important foundations of target information processing. We have made significant contributions in this aspect. More specifically, we have developed a new framework for state estimation with point and set measurements that can handle effectively many diverse applications, including particularly many practical problems in target information processing. Highly related with this new framework, we also investigated estimation and filtering for Gaussian variables with linear inequality constraints. This has important applications in ground (especially on-road) target tracking.

The states of some dynamic systems satisfy certain constraints arising from physical laws, mathematical properties, or practical constraints. A typical example is ground target tracking on a road network. We have made significant contributions in several aspects of this important topic. First, we have proposed several algorithms in different forms of the linear minimum mean square estimator for this problem. They are all optimal in the linear class. Second, we have developed a general method to construct an unconstrained dynamic model that is mathematically equivalent to the original system with constraints, thus simplifying the constrained problem to an unconstrained problem. This model has several important desirable properties, including clear physical interpretation and high computational efficiency. Third, we have made an important finding: under certain conditions, although equality constraints are indispensable in the evolution of the state, update by them is redundant in optimal filtering; however, if there is model mismatch, update by equality constraints is necessary and helpful. Fourth, unlike the existing system conversion based design techniques, we propose a new systematic way to design and analyze linear equality constrained linear dynamic systems through a direct elimination technique, where the desired model class is given and only the distribution of the initial state and driven process noise needs to be determined. This method is comparatively much easier. We also found that the existing formulations of linear equality constrained linear dynamic systems only cover a small part of the whole class.

Based on our work in these areas, we have also developed algorithms and designs for aided strapdown inertial navigation for autonomous underwater vehicles. This was a practical project funded by the Naval Oceanographic Office.

Data Fusion for Estimation

Estimation fusion is data fusion for the purpose of estimating some quantity, usually a parameter or a process. It is an essential part of target information processing when multiple sensors are used. Abundant results in this area have been obtained. They include several aspects.

- Optimal fusion requires knowledge of cross-correlation. Unfortunately, this knowledge is sometimes unavailable in practice. In view of this, we have developed

three fault-tolerant fusion rules for this case: fast covariance intersection, generalized convex combination, and analytic center approach.

- We have proposed several compression rules for sensor data based on which optimal distributed fusion will have performance that is globally optimal under fairly general conditions.
- We have developed optimal LMMSE fusion in the form of quasi-tracklets to handle cross-correlated cases, along with analysis of its performance and presentation of necessary and sufficient condition for its optimality.
- Estimation fusion for the case of multiple dynamic and/or measurement models was never considered before due to its complexity. We have successfully developed several such fusers.
- Almost all existing fusion results rely on some level of probabilistic or statistical description of the problem, which is not available or appropriate in some cases. With this understanding, we proposed a new formulation in the H-infinity setting, which is robust against descriptions and assumptions, and successfully developed several corresponding rules for centralized and distributed fusion, which is applicable even to nonlinear delayed systems with multiple sensors.
- Besides fusion results for filtering, we have also obtained theoretical results for fusion for optimal smoothing, which has been largely overlooked so far by the fusion community.

UAV Team Path Optimization for Search and Track

To better serve the Army's mission, one application focus of the project is path planning of a team of unmanned aerial vehicles (UAV) for joint detection, localization, and tracking of multiple targets. Another is ground target tracking—track an uncertain number of possibly crossing targets using data transmitted from multiple sensors (e.g., imagers and radars) onboard a moving platform as well as topographic information such as road maps.

Most UAV team missions have a dual purpose of search and surveillance, which entails not only finding, but also monitoring of targets, including their locations and motions. Among the central topics of UAV missions is path planning for search and surveillance. It is vastly different from the traditional path planning (e.g., in robotics), which is largely a “how-to-go-from-A-to-B” problem. Traditional search or tracking theoretic approaches based on optimizing detection probability or estimation error would not meet the diverse, competing needs of a UAV mission. Unlike existing path planning of a cooperative UAV team, which handles the competing objectives in a piecemeal manner, we took a systematic JDE approach: we proposed a solution based on the introduction of a new performance index—gain in the information value—which permits naturally joint optimization of the objectives of target detection, target tracking, and vehicle survivability nicely for search and track missions.

More recently, we have obtained significant theoretical results for dynamic re-planning of the UAV team path for detection, localization, and tracking that is capable of adapting to real-time changes in the command, intelligence, environment, etc. These results are

significantly more solid than existing ones. In a dynamic situation, events that call for a change of the plan may occur, including the arrival of a new command or intelligence, detection of a new target, loss of a UAV, a sudden change of weather, etc. Therefore, an appropriate time horizon for re-planning must be determined. If it is too long or too short, the updated plan may be poor. There is little research, if any, regarding the determination of the optimal planning horizon. We have initiated a theoretical study of this important topic. Our work presents a planning horizon that is optimal in the sense of minimizing errors in planning time. It is intended for the use in mission planning but has many other applications.

Technically, UAV path planning for target detection, localization, and tracking is a problem of constrained multiple-objective optimization. As is well known, there is an optimal set (i.e., Pareto front) in which each point corresponds to a certain tradeoff among the values of the objective functions. Solutions to such a problem are not unique in general. Which of the many Pareto optimal points is the “best trade-off”? A decision is needed as to which Pareto optimal point provides the best tradeoff among all alternatives. A natural approach is to optimize a convex combination of the individual objectives. We have developed such a solution for cooperative UAV path optimization, along with an efficient method of getting the weights from the Pareto optimal points. We are developing methods based on a special scalar objective function that suits particularly well to our problem of UAV path optimization for joint detection, localization, and tracking of multiple targets.

Multiple-Model Approach

The multiple-model (MM) approach can be treated as a special case of the joint decision and estimation (JDE) approach, which is the focus of this project. It provides the state-of-the-art solutions to many problems involving estimation, filtering, control, decision, and/or modeling. It has three generations: autonomous MM, cooperating MM, and variable-structure MM (VSMM), of which the VSMM is the most advanced and powerful. Significant results have been obtained in several aspects.

- We have developed three new VSMM approaches: (a) best-model augmentation (BMA), (b) hybrid grid, and (c) second-order Markov chain. BMA is a general and promising new VSMM algorithm. It is a generalization of the well-regarded expected-mode augmentation (EMA) algorithm developed by us before. It is applicable whenever EMA is and they are virtually the same. BMA still applies when EMA does not, such as when models have different structures. The hybrid-grid approach uses a model set that is a combination of a fixed coarse grid and an adaptive fine grid. The second-order Markov chain based multiple-model algorithms developed is particularly suitable for maneuvering target tracking.
- Perhaps the most important task in the application of the MM approach is the design of model set. We have also made significant progress in this aspect. We have proposed two model-set design methods. The uniform model set design is based on number theory and has general applicability. The second, moment-matching based approach is particularly suited to the hybrid-grid approach to MM estimation developed recently.

- Taking advantage of the great power of the MM approach, we have also formulated the problem of fault detection and isolation in the MM setting and provided a solution that outperforms by far existing ones. This has been done for vastly different applications: (a) sensor, actuator, or system faults of an aircraft (b) heating, air conditioning, and ventilation (HAVC) in building automation and (c) machine wear prognostics and remaining useful life prediction.
- In addition, we have obtained significant results for distributed MM fusion, that is, fusing local estimates obtained based on multiple dynamic models.

Evaluation of Decision and Estimation Algorithms

Science and engineering abound in algorithms for decision or estimation. However solid such an algorithm is in theory, its performance and characteristics must be evaluated in practice to serve a number of purposes, such as verification of its validity, demonstration of its performance, and comparison with other solutions.

We have developed a novel, theoretically solid approach to performance evaluation that is general, comprehensive, and straightforward to implement without the need to know the ground truth. It can always rank very different decision algorithms objectively; it has no difficulty for cases with two or more choices (or hypotheses), misspecification (i.e., the truth is not one of the hypotheses), and/or where hypotheses are composite (i.e., having unknown parameters); and it does not need to know the functional form of the truth or hypotheses. This is a very significant development. It is potentially a breakthrough in decision performance evaluation. Past and existing measures of decision performance are seriously flawed or limited. Our method is the only one known to us that overcomes many difficulties (including all those listed above) naturally and easily.

We have developed an array of metrics that measure absolute or relative performance of estimation. They suit different applications. We have clarified widespread misuse of and misconception about the most popular estimation metric: root-mean-square error. We have also introduced an important concept of optimism, pessimism, and neutralism to characterize many estimation performance metrics regarding whether they focus on good or bad performance. We have also initiated the study of comprehensive measures of estimation performance evaluation. The practical value of these largely theoretical developments has been quickly recognized by the target information processing community. For example, based on his team's comparative studies, Dr. Erik Blasch of Air Force Research Laboratory appraised highly of the practical value of our work on performance evaluation metrics for data fusion and target tracking and classification.

Most estimators and filters provide assessments of their own estimation errors, often in the form of mean-square error and bias. Are these self-assessments trustable? What is the degree to which they are trustable? We have raised such questions formally, referred to as credibility of estimators, formulated the problem theoretically, and provided two types of solutions: credibility tests for qualitative questions of the first kind and credibility measures for quantitative questions of the second kind. These results are significant. They address an important practical problem of estimation that has been largely

overlooked in theory but are badly needed in practice. We have also shown that one of the credibility measures developed is truly a distance metric and have good application in many areas outside credibility evaluation, such as statistics, data fusion, matrix theory, and general data driven performance evaluation.

We also applied theoretical study in performance metrics and statistical inference algorithms to haplotype inference problem in bioinformatics, orbital evasive target tracking and sensor management in space situational awareness, joint identification and tracking of contaminate clouds, remaining useful life prediction of battery and other mission critical components in fault prognosis.

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2. J. Lan and X. R. Li, "Equivalent-model augmentation for variable-structure multiple-model estimation," submitted as a regular paper to *IEEE Transactions on Aerospace and Electronic Systems*, 2012
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1. Y. Liu and X. R. Li, "Average run length function of Page's CUSUM test with independent but non-stationary log-likelihood ratios," submitted to 51th Conference on Decision and Control, Maui, Hawaii, USA, December 10–13, 2012
2. Y. Liu and X. R. Li, "Operating characteristic and average sample number functions of truncated sequential probability ratio test," submitted to 15th International Conference on Information Fusion, Singapore, 9–12 July 2012
3. R. Pitre and X. R. Li, "Minimum time-error planning horizon for plan updating triggered by Poisson random events," submitted to 15th International Conference on Information Fusion, Singapore, 9–12 July 2012
4. J.-L. Sun, J. Zhou, and X. R. Li, "State estimation for systems with unknown inputs based on variational Bayes method," submitted to 15th International Conference on Information Fusion, Singapore, 9–12 July 2012

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8. H.-L. Yin, J. Lan, and X. R. Li, "New robust metrics of central tendency for estimation performance evaluation," submitted to 15th International Conference on Information Fusion, Singapore, 9–12 July 2012
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N/A

Book Chapters:

1. A. Bashi, V. P. Jilkov, and X. R. Li, "Nonlinear estimation and fault detection for large scale industrial HVAC systems," in *Nonlinear Estimation and Applications to Industrial Systems Control*, G. Rigatos (Ed.), Nova Publisher, 2012
2. H. Chen, Z. Zhao, K. Zhang, and D. Zhu, "New aspects of haplotype inference from SNP fragments," in *A Practical Guide to Bioinformatics Analysis*, G. P. C. Fung (Ed.), iConcept Press, 2010, pp. 173–183
3. H. Chen, G. Chen, D. Shen, E. Blasch, K. Pham, "Orbital evasive target tracking and sensor management," in *Dynamics of Information Systems: Theory and Applications*, M. J. Hirsch, P. M. Pardalos and R. Murphey (Eds.), Chapter 12, Springer Lecture Notes in Control and Information Sciences, 2010, pp. 233–255

Honors and Awards:

The PI, Dr. X. Rong Li, was selected as Chancellor's University Research Professor by the University of New Orleans in the second year of this project, which is one of the highest academic honors that the University of New Orleans can give.

The two co-PIs, Drs. Vesselin Jilkov and Huimin Chen, were both granted tenure and promoted to Associate Professor by the University of New Orleans in the second year of this project.

Number of Patents Disclosed: 0

List of patent titles disclosed

Number of Patents Awarded: 0

List of patent titles awarded:

Technology Transfer (any specific interactions or developments which would constitute technology transfer of the research results). Examples include interaction with other DOD scientists, interactions with industry, initiation of a start-up company based on research results or transfer of information which might impact the development of products.

We have been and are collaborating with several small business companies for technology transfer. Several joint SBIR/STTR proposals for such collaboration have been submitted, based partially on results from a former ARO project and this ARO project. Two of them were successful:

- "Multiple Target Tracking of Objects Exhibiting Significant Nonlinearities," jointly with ObjectVideo, Inc., funded by Air Force Research Lab in the amount of \$150,000 for Phase I.
- "An Integrated Constellation Sensor Simulation Environment for Airborne ISR," jointly with DCM Research Resources, LLC, funded by the Air Force Research Lab in the amount of \$100,000 for Phase I.

Research results of a former ARO project and this ARO project have been applied to this SBIR project. We have active ongoing collaboration with many researchers elsewhere, including DoD labs, DoE lab, and numerous companies. We are actively seeking collaboration with researchers at Army, Navy, and Air Force R&D facilities.

Based on the research of this ARO project, we have also secured the following funded research projects:

- A research project titled "Coordinated Search and Surveillance by a UAV Team" on the development of flight path optimization and control of a coordinated UAV team for search and track missions, funded by the Department of Homeland Security in the amount of \$200,000 for 20 months. The project, led by us, is a team work with QinetiQ North America and the Ben-Gurion University of Israel. The cornerstone of the project is the introduction of an expected information gain as the objective function. It is a special case of the general JDE method developed in the ARO project, tailored particularly for UAV search and track missions.
- The study on nonlinear filtering techniques, particularly its application in maneuvering target tracking, supported by this ARO project forms part of the basis for the three-

year project titled “High Performance Parallel & Distributed Algorithms for Nonlinear Particle Filtering,” funded by Louisiana Board of Regents in the amount of \$109,143.

- Based on our work in these areas, we have developed algorithms and designs for aided strapdown inertial navigation for autonomous underwater vehicles. This was a practical project funded by the Naval Oceanographic Office in the amount of \$100,000 for one year. The performance evaluation results obtained in this project was critical in evaluating the navigation performance of this project.

Number of Graduate Students Supported: 10

Names of Graduate Students and percentage each is supported:

Ashwini Amara, 1
Sowmya Bandrupalli, 0.5
Xiaomeng Bian, 0.5
Yangsheng Chen, 1
Zhansheng Duan, 0.5
Jaipal Katkuri, 0.5
Gang Liu, 0.3
Ryan Pitre, 0.5
Rastin Rastgoufard, 0.5
Harika Rao Vamulapalli, 0.3

Total of percentages for graduate students above: 5.6

Number of Post Doctorates Supported: 0

Names of Post Doctorates and percentage each is supported:

Total of percentages for Post Doctorates above: 0

Number of Faculty Supported: 3

Names of Faculty:

X. Rong Li
Vesselin P. Jilkov
Huimin Chen

Number of Other Research Staff Supported: 0

Names of Other Research Staff Supported:

Number of Under Graduate Students Supported: 0

Names of Under Graduate Students:

Number of PHDs Awarded: 2

Names of personnel receiving PHDs:

Zhansheng Duan
Ryan Pitre

Number of Master Degrees Awarded: 6

Names of personnel receiving Masters:

Sowmya Bandarupalli
Ashwini Amara
Harika Rao Vamulapalli
Jaipal Katkuri
Yangsheng Chen
Gang Liu